

Electroweak baryogenesis in a scale invariant model and Higgs phenomenology ^a

Kaori Fuyuto¹ and Eibun Senaha^{1,2 b}

¹*Department of Physics, Nagoya University, Nagoya 464-8602, Japan,*

²*Department of Physics and Center for Mathematics and Theoretical Physics, National Central University, Taoyuan, 32001, Taiwan*

We study the electroweak phase transition and the critical bubble in the scale-invariant two Higgs doublet model taking the recent LHC data into account. The sphaleron energy in this model is evaluated for the first time. It is found that the strong first-order electroweak phase transition is the inevitable consequence to be consistent with the observed 125 GeV Higgs boson. In such a case, the signal strength of the Higgs decay to two gammas and the triple Higgs boson coupling could deviate from the SM values by -10% and $+82\%$, respectively.

1 Introduction

Establishment of the Higgs sector is one of the primary issues in particle physics. In 2012, a scalar boson was discovered at the Large Hadron Collider (LHC), and the mass of the particle has been determined with 0.2% accuracy, $m_H = 125.09 \pm 0.21$ (stat.) ± 0.11 (syst.) GeV ¹. Clarifying the properties of the particle is as important as its discovery since the discovered particle must have the important roles if it is really the Higgs boson, namely, the origins of the mass generation and the electroweak symmetry (EW) breaking. The experimental proof of the former is possible by measuring the Higgs boson couplings to the gauge bosons and the fermions precisely, and the LHC experiment is now accessing those couplings. The latter can be clarified by reconstructing the Higgs potential. In particular, the measurement of the triple Higgs boson coupling is enormously important since it can exist only after EW symmetry is broken. So far, we know much less about the Higgs potential.

The EW symmetry can be broken if a tachyonic mass arises, which applies in the standard model (SM). On the other hand, as pointed out by Coleman and Weinberg², quantum corrections could also induce the EW symmetry breaking in massless theories. One of the cosmological implications of such classical scale-invariant theories is that the EW phase transition (PT) is first order, which is needed for successful EW baryogenesis (BG)³. As explicitly demonstrated by Funakubo et al, the scale-invariant two Higgs doublet model (SI-2HDM) accommodates the strong first-order EWPT⁴. However, in their analysis the masses of the Higgs boson and the top quark were not fixed to their observed values since those particles were not discovered at that time.

In this talk, we update the previous analysis in the light of the LHC data, and briefly discuss the phenomenological consequences in connection with Higgs physics.⁵

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^bspeaker

2 Model

The Higgs potential in the SI-2HDM is given by⁶

$$V_0 = \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right], \quad (1)$$

where the mass terms are forbidden by the classical scale invariance, and Z_2 symmetry is imposed to avoid the Higgs-mediated flavor-changing neutral current processes at tree level. From the stationary conditions, one gets

$$\tan^2 \beta = \left(\frac{v_2}{v_1} \right)^2 = \sqrt{\frac{\lambda_1}{\lambda_2}}, \quad \sqrt{\lambda_1 \lambda_2} + \lambda_{345} = 0, \quad (2)$$

where $v_1 = v \cos \beta$ and $v_2 = v \sin \beta$ with $v \simeq 246$ GeV, and $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$. We analyze the radiative EW symmetry breaking along the flat direction using the Gildener-Weinberg method⁷. The tree-level effective potential is

$$V_0(\varphi_1, \varphi_2) = \frac{\lambda_1}{8}\varphi_1^4 + \frac{\lambda_2}{8}\varphi_2^4 + \frac{\lambda_{345}}{4}\varphi_1^2\varphi_2^2, \quad (3)$$

where $\varphi_{1,2}$ are the classical background fields. Eq. (2) indicates that the energy of the minimum of V_0 is zero. Furthermore, from Eq. (2), it follows that the determinant of the mass matrix of the CP-even Higgs bosons is zero. Therefore, the tree-level potential has the flat direction. The massless scalar is the consequence of the classical scale invariance. The Higgs boson mass is generated after the EW symmetry is broken. Explicitly, one finds

$$m_h^2 = \frac{1}{8\pi^2 v^4} \left[m_H^4 + m_A^4 + 2m_{H^\pm}^4 + 6m_W^4 + 3m_Z^4 - 12(m_t^4 + m_b^4) \right]. \quad (4)$$

Note that m_h^2 becomes negative if the heavy Higgs bosons (H , A , H^\pm) are absent.

3 Sphaleron and Critical bubble

In the EWBG mechanism, the baryon number (B) is created by expanding Higgs bubbles. B can survive after the EWPT if the sphaleron process in the broken phase is quenched. Here, as the sphaleron decoupling condition, we adopt $\Gamma_B^{(b)}(T) \simeq (\text{prefactor})e^{-E_{\text{sph}}(T)/T} < H(T)$, where $\Gamma_B^{(b)}$ denotes the sphaleron rate in the broken phase, which is exponentially suppressed by $E_{\text{sph}}(T)/T$, with $E_{\text{sph}}(T)$ being the sphaleron energy at a temperature T . $H(T)$ is the Hubble parameter at T . We parametrize the sphaleron energy as $E_{\text{sph}}(T) = 4\pi v(T)\mathcal{E}(T)/g_2$, where g_2 denotes the SU(2) gauge coupling constant. The sphaleron decoupling condition then takes the form

$$\frac{v(T)}{T} > \frac{g_2}{4\pi\mathcal{E}(T)} \left[42.97 + \log \text{ corrections} \right] \equiv \zeta_{\text{sph}}(T). \quad (5)$$

The log corrections mainly come from the fluctuation determinants about the sphaleron configuration, which will be dropped in our numerical evaluation of ζ_{sph} since they are subleading. We evaluate v_C/T_C and $\zeta_{\text{sph}}(T_C)$ numerically, where T_C is a temperature at which the effective potential has two degenerate vacua, and v_C is the Higgs vacuum expectation value at T_C . (For a recent study on $\zeta_{\text{sph}}(T_C)$ in the SM with a real singlet scalar, see Ref.⁸.)

If the supercooling is large, the use of the above criterion would not be appropriate. As is done in the previous study, we also estimate a nucleation temperature (T_N), which is defined by

$$\Gamma_N(T_N)/H^3(T_N) = H(T_N), \quad (6)$$

where Γ_N is the bubble nucleation rate per unit volume per unit time at T_N . It should be emphasized that it is impossible to convert the entire region into the broken phase by only one

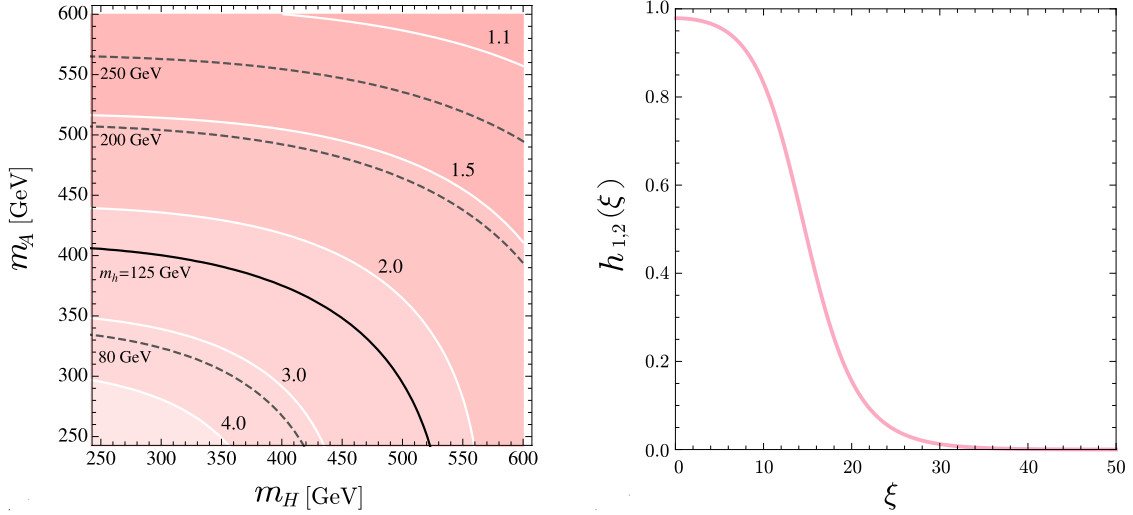


Figure 1 – (Left panel) Contours of m_h and v_C/T_C in the (m_H, m_A) plane. The solid line in black represents $m_h = 125$ GeV. The each contour in white shows $v_C/T_C = 1.1, 1.5, 2.0, 3.0$ and 4.0 from top to bottom. (Right panel) The bubble wall profile at T_N .

bubble nucleated within the horizon volume. Therefore, the nucleation temperature defined by Eq. (6) should be thought as an upper bound of the temperature at which the EWPT develops.

In studying Eqs. (5) and (6), we use the following resummed effective potential

$$V_{\text{eff}}(\varphi, T) = \sum_i n_i \left[\frac{\bar{M}_i^4(\varphi, T)}{64\pi^2} \left(\log \frac{\bar{M}_i^2(\varphi, T)}{\bar{\mu}^2} - c_i \right) + \frac{T^4}{2\pi^2} I_{B,F} \left(\frac{\bar{M}_i^2(\varphi, T)}{T^2} \right) \right], \quad (7)$$

with $I_{B,F}(a^2) = \int_0^\infty dx \, x^2 \log \left(1 \mp e^{-\sqrt{x^2 + a^2}} \right)$, where $\bar{M}_i^2(\varphi, T)$ are the field-dependent boson masses with thermal corrections⁵.

4 Results

In the left panel of Fig. 1, m_h and v_C/T_C are plotted in the (m_H, m_A) plane. As seen from Eq. (4), m_h goes up according as the heavy Higgs boson masses increase. The black solid line corresponds to $m_h = 125$ GeV. In other words, the 125 GeV Higgs predicts the scale of the heavy Higgs bosons. We overlay v_C/T_C denoted by the white contours. From top to bottom, $v_C/T_C = 1.1, 1.5, 2.0, 3.0$ and 4.0 . It is concluded that the 125 GeV Higgs boson inevitably leads to the strong first-order EWPT in the SI-2HDM.

In the right panel of Fig. 1, the bubble wall profile at T_N is shown. Unlike the minimal supersymmetric SM case⁹, the bubble wall width is thinner in the SI-2HDM.

As a benchmark, we take $m_H = m_A = m_{H^\pm} = 382$ GeV. Our findings are listed in Table 1. The sphaleron decoupling condition is satisfied at T_N . In this case, the signal strength of the Higgs boson decay to 2 gammas ($\mu_{\gamma\gamma}$) is reduced by 10% owing to the charged Higgs boson loop¹⁰, and the deviation of the hhh coupling from the SM value ($\Delta\lambda_{hhh}$) is about +82%. The more detailed discussions on the phenomenology may be found in Refs.^{11,12}.

5 Summary

In this talk, the EWPT and the critical bubble in the SI-2HDM were revisited in the light of the LHC data. We also estimated the sphaleron decoupling condition in this model for the first time. To be consistent with 125 GeV Higgs boson, the EWPT is inevitably strongly first order. Some of phenomenological consequences of this model are $\mu_{\gamma\gamma} = 0.9$ and $\Delta\lambda_{hhh} = +82.1\%$.

v_C/T_C	211 GeV/91.5 GeV = 2.31
$\zeta_{\text{sph}}(T_C)$	1.23
v_N/T_N	229 GeV/77.8 GeV = 2.94
$\zeta_{\text{sph}}(T_N)$	1.20
$E_{\text{cb}}(T_N)/T_N$	151.7
κ_V	1.0
κ_f	1.0
$\mu_{\gamma\gamma}$	0.90
$\Delta\lambda_{hhh}$	82.1%
Λ	6.3 TeV

Table 1: The results in our benchmark scenario ($m_H = m_A = m_{H^\pm} = 382$ GeV) are summarized. For the evaluation of the cutoff scale Λ , $\tan\beta = 1$ is chosen as a reference value.

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References

1. Georges Aad et al. Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments. 2015.
2. Sidney R. Coleman and Erick J. Weinberg. Radiative Corrections as the Origin of Spontaneous Symmetry Breaking. *Phys.Rev.*, D7:1888–1910, 1973.
3. V.A. Kuzmin, V.A. Rubakov, and M.E. Shaposhnikov. On the Anomalous Electroweak Baryon Number Nonconservation in the Early Universe. *Phys.Lett.*, B155:36, 1985.
4. Koichi Funakubo, Akira Kakuto, and Kazunori Takenaga. The Effective potential of electroweak theory with two massless Higgs doublets at finite temperature. *Prog.Theor.Phys.*, 91:341–352, 1994.
5. Kaori Fuyuto and Eibun Senaha. Sphaleron And Critical bubble in a scale invariant model : ReAnalysis. 2015.
6. Kenzo Inoue, Akira Kakuto, and Yoshimasa Nakano. Perturbation Constraint on Particle Masses in the Weinberg-Salam Model With Two Massless Higgs Doublets. *Prog.Theor.Phys.*, 63:234, 1980.
7. Eldad Gildener and Steven Weinberg. Symmetry Breaking and Scalar Bosons. *Phys.Rev.*, D13:3333, 1976.
8. Kaori Fuyuto and Eibun Senaha. Improved sphaleron decoupling condition and the Higgs coupling constants in the real singlet-extended standard model. *Phys.Rev.*, D90(1):015015, 2014.
9. Koichi Funakubo and Eibun Senaha. Electroweak phase transition, critical bubbles and sphaleron decoupling condition in the MSSM. *Phys.Rev.*, D79:115024, 2009.
10. Ilya F. Ginzburg, Maria Krawczyk, and Per Osland. Two Higgs doublet models with CP violation. 2002.
11. Christopher T. Hill. Is the Higgs Boson Associated with Coleman-Weinberg Dynamical Symmetry Breaking? *Phys.Rev.*, D89(7):073003, 2014.
12. G.C. Dorsch, S.J. Huber, K. Mimasu, and J.M. No. Echoes of the Electroweak Phase Transition: Discovering a second Higgs doublet through $A_0 \rightarrow ZH_0$. *Phys.Rev.Lett.*, 113(21):211802, 2014.